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# The Oxygen Isotope Composition of Ice Wedges of Ayon Island and Paleotemperature Reconstructions of the Late Pleistocene and Holocene of the Northern Chukotka

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**Abstract**—Syngenetic ice wedges have been investigated on Ayon Island. Their isotope composition and the geochemical characteristics of both ice wedges and enclosing sediments have been obtained; four ice-wedge stages have been distinguished. Paleo temperature reconstructions for Ayon Island and adjacent territories of northern Chukotka have been obtained based of these results. Almost identical trends in the distribution of ice-wedge isotope characteristics in the Arctic islands and in the lower reaches of the Kolyma River were observed, as well as differences in the magnitude of isotope oscillations during the transition from the Late Pleistocene to the Holocene compared to ice wedges of the Lower Kolyma region.

*Keywords:* Ice wedge, Holocene, Late Pleistocene, stable isotope, heavy oxygen, deuterium, Ayon Island, Chaun-Chukotka

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## INTRODUCTION

The first mention of Ayon Island is linked with the name of the explorer Isaya Ignat'ev, who landed on its coast in 1646. However, the geological and geocryological knowledge of the island is weak. A 671-m borehole was drilled in 1980 on the surface of the Late Pleistocene terrace on the northwestern coast of Ayon Island with 55 to 64 m levels; it exposed the fullest section of Cenozoic rocks for the East Siberian Sea shelf. Different age interpretations resulted from the same parts of the borehole section, especially the upper part based on the analysis of foraminifers (Gudina et al., 1984), diatoms (Stepanova, 1989), spores, and pollen (Karevskaya et al., 1984). Special geocryological aspects of Ayon Island were schematically considered only by A.A. Svitoch et al. (*Noveishie otlozheniya*..., 1980; Svitoch et al., 1978) and incompletely in our works (Vasil'chuk, 1989, 1992).

There is lack of fully studied key sections of the Late Pleistocene permafrost with ice wedges in the north and west of Chukotka adjacent to Ayon Island. They were described at four sites (Figs. 1a, 1b): Ayon Island, Rauchua River mouth, Wrangel Island, Amguema River valley and its tributary Ekitiki River, as well as in the basin of the El'gygydgyn lake (Kotov, 1997, 1998, 1999a, 1999b; Schwamborn et al., 2006).

## OBJECTIVES OF THE STUDY

The goal of our work was to consider the features of the cryolithological structure of the Late Pleistocene and Holocene ice wedges of Ayon Island: to interpret the data of their isotope-oxygen composition, radiocarbon dates, and hydrochemical characteristics, to compare them with the data on nearby areas, and to assess changes in paleogeocryological and paleoclimatic conditions in the north of Chukotka in the late Pleistocene and Holocene.

**The location of the yedoma strata.** Ayon Island, with an area of 2000 km$^2$, is located in the eastern part of the Kolyma Bay (Fig. 1a). Its length is 63 km, its width is 38 km, and the altitude is up to 64 m. Ayon Island is separated from the continent by the shallow Malyi Chaun Channel with a width of approximately 2 km. Since March 21, 1942 the Sidorov hydrometeorological station (69°56′12″ N, 67°59′40″ E) has operated on the island.

The vegetation of the island has transitional characteristics: from the northern hypoarctic tundra to the arctic with steppificated cryophytic, tundra-steppe communities; sedge–hyphnum bog associations occur in depressions. The mean annual air temperature at Ayon is −11.4°C; the long-term mean annual

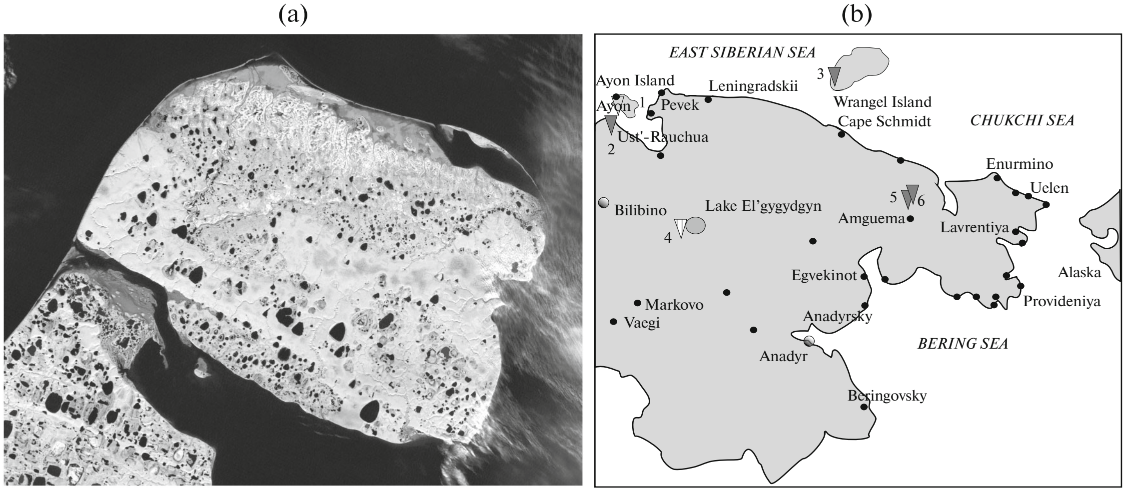


**Fig. 1.** Ayon Island on the satellite image with clearly defined polygonal relief (a) and the studied areas of the Late Pleistocene and Holocene ice wedges in the north and west of Chukotka (b): 1, Ayon Island; 2, the mouth of the Rauchua River, 3, Wrangel Island; 4, Lake El'gygytgyn; 5, Ekityki River; 6, the middle reaches of the Amguema River.

temperature is −29°C for January, −20°C for winter, and approximately +8°C for July.

Ayon Island has widely distributed polygonal relief. Practically regular tetragons have been formed in the river valleys in uniform sandy–loamy deposits with their outlines following the aligning surfaces. Hexagonal forms predominate in homogeneous rocks without orienting surfaces. The frost polygons vary from 6–8 to 20–30 m (see Fig. 1a) there. The ice wedges on Ayon Island have been mainly formed during the last 30000 years and the process of ice-wedge formation still continues. The yedoma deposits were studied on the west coast of Ayon at the large exposure of the 30–40-m terrace on the coast of the East Siberian Sea. A polygonal relief with isometric polygons of 5 × 8 m is developed there.

**Cryogenic structure.** The main part of the yedoma is composed of dark brown, blue-gray to gray high-ice sandy loam (Table 1), with a characteristic yedoma smell. The thickness of the sandy loam exceeds 25 m almost everywhere with a multi-layered polygonal-ice-wedge complex cutting through vertically. Four cyclites occur in the yedoma emphasized by four levels of ice wedges. In the upper part of the section (18–23 m) narrow saberlike veins of the first level 3–4 m a.s.l. and 1.2–1.5 m in width, are intruded into the wider wedges of the lower level (13–18 m a.s.l.). The width of the wedges of the second level does not exceed 1.5–2 m; the distance between them is 5–8 m. These wedges expand the wider wedges of the lower third level (8–13 m a.s.l.) with their bottom parts. The transition from the second to the third level is not expressed, since often the "veins" of the second level are located next to the heads of the wedges of the third level. The wedges of the third level are also not wide (approximately 2–2.2 m). The lowest layer of ice wedges is the fourth occurring from 5 to 8 m, the ice wedges of this level are narrower, from 1 to 1.5 m, and they are composed of vertically-striped gray ice.

Earlier studies of the Ayon yedoma also fixed four levels of ice wedges (*Noveishie otlozheniya*..., 1980). The "veins" of the ice wedges of the bottom parts penetrate into the yellow sands that underlie the yedoma deposits. A sandy formation lies at the base of the terrace with a shallow dome. The top of the sand rises from 4 m above sea level on the edges of the dome to 8–9 m in its center, the dome stretches along the coast for more than 5 km. In these sands, a complex of freshwater mollusks living in stagnant reservoirs was found (*Noveishie otlozheniya*..., 1980), which leads to the conclusion that the sands accumulated in a freshwater reservoir. In the outcrop of the thermokarst (alas) depression, peat (alas) is exposed on the surface of the yedoma, which is underlain by gray and brown sandy loam and contains Holocene ice wedges with a 3-m height.

**Sampling for analytical studies.** The yedoma and the late Pleistocene ice wedges, as well as the Holocene lacustrine-bog sediments and Holocene ice wedges, were tested for isotope, chemical, enzymatic, and radiocarbon analyses (Fig. 2). The content of pollen and spores was determined in ice wedges. The roots of grasses were sampled for radiocarbon dating from the yedoma sediments because they are the most reliable material for homogeneous strata dating, since they occur in a section in situ. Samples for isotope analysis were selected according to the unified method (Vasil'chuk, 1992). For isotope analysis, ice samples were taken from the axial parts of the ice wedges, with an interval of 0.2–0.5 m. Both the largest ice wedges, along with the small ones in the upper and lower parts of the strata, as well as textured ice were tested (Fig. 3).

**Table 1.** The composition of deposits and cryogenic structure of Late-Pleistocene Yedoma and Holocene peat strata of Ayon Island

| Depth, m | Composition of deposits | Cryogenic structure | Features of cryogenic structure |
|---|---|---|---|
| Ayon Island, west coast, yedoma on the coast of East Siberian Sea, the altitude of 37 m a.s.l. (the point 337-YuV), Chaun-Chukotka | | | |
| 0–0.5 | Pale-brown, strongly-sandy peat bedded due to interbedding of more and less sandy beds | Thawed | |
| 0.5–2.0 | Black and dark-brown peat with a small admixture of loamy sand | Massive and scarcely-bedded | |
| 2.0–3.0 (sometimes up to 5.0) | Pale-gray, light sandy loamy sand | Basal and bedded | Strongly icy |
| 3.0 (5.0)–25.0 | Dark-brown loamy sand with a small admixture of roots of the plants, occasionally with patches of peat or coprolites | Massive and fine-mesh | Schlieres up to 0.5 cm thick |
| 25.0–37.0 | Grayish-yellow sand with rare fauna of marine borers | Massive | |
| Ayon Island, west coast, a peat patch in the upper part of the yedoma on the coast of the East Siberian Sea (point, 337-YuV), Chaun-Chukotka | | | |
| 0.0–0.35 | Brown somewhat decomposed dry peat | Thawed | |
| 0.35–1.9 | Brown solidly frozen peat | Massive and scarcely-bedded | Strongly-icy |
| 1.9–3.1 | Gray light loamy sand | Massive | Icy |

## RESULTS AND DISCUSSION

Radiocarbon dates were obtained for the upper and lower parts of the homogeneous yedoma strata. The dating material consisted of roots. The dating of roots of grasses in the absence of other organic macrofossils allows one to obtain quite reliable dates (Murton et al., 2015; Vasil'chuk, 1992). The roots at 8.5 m are dated as 28.6 ka, at 9 m, 28.1 ka, and at an altitude of 30.5 m, 10 ka (Fig. 3, Table 2). Thus, the yedoma had been accumulated in the late Pleistocene in the time interval from 30 to 10 ka BP (BP).

Based on the obtained data, by interpolation, the lower fragment of the section, including the lowest fourth level of ice wedges, may have an age in the range of 30 to 26 ka BP. The $\delta^{18}O$ values are from –34.0 to –30.3‰, with the mean value of –31.15‰ (Table 3) there. The distribution of values is contrasting; the beginning of the wedge accumulation of this level is probably associated with a very cold period, since the lowest value of the heavy oxygen isotopes (–34‰) is noted here.

A fragment of the section contains the thickest wedges of the third level, which were assumed to be formed from 26 to 20 ka BP. The lowest values (–33‰) occur at +13 m. The mean value of $\delta^{18}O$ in wedges of this level is –31.6‰.

The period of formation of ice wedges of the second level is estimated as 15 to 20 ka BP. The fluctuations in the isotope composition are 3‰ (from –32 to –29‰). The distribution is contrasting, but the content of heavy oxygen isotopes is higher than in the first and second levels in general; the mean value of $\delta^{18}O$ in wedges of this level is –30.5‰. The wedges of the upper (first) level are characterized by a relatively high content of heavy oxygen isotopes; the mean value of $\delta^{18}O$ in this fragment is –29.3‰.

The Holocene lacustrine-bog inset with ice wedges has a height of more than 3 m (Fig. 4) and is located at the top of the section. The values of $\delta^{18}O$ in Holocene ice wedges are practically stable (from –21.0 to –22.3‰); the most negative values are noted for the upper parts of the wedges, while the rim of the Holocene ice

**Fig. 2.** Sampling for isotope-geochemical analyses from the Late Pleistocene syngenetic ice wedge of Ayon yedoma. Photo by Yu.K. Vasil'chuk.

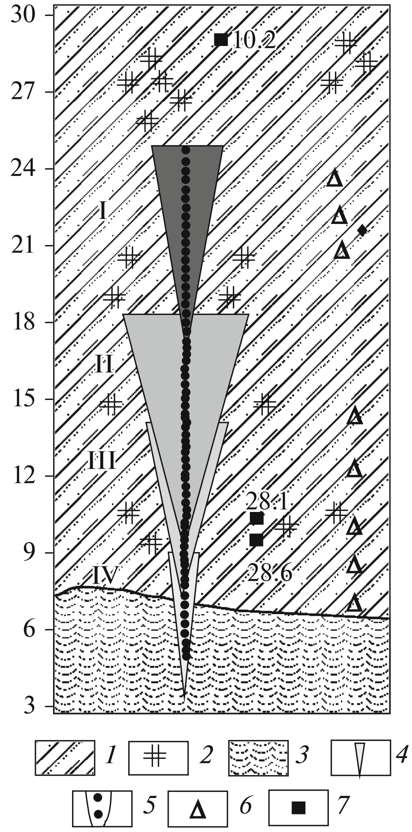


**Fig. 3.** The scheme of sampling in the Late Pleistocene section, cryolithological structure of the Late Pleistocene ice complex on Ayon Island: (*1*) sandy loam; (*2*) rootlets and allochthonous detritus; (*3*) sand; (*4*) ice-wedge; (*5–7*) sampling points: (*5*) for isotope-oxygen analysis from ice wedges, (*6*) for isotope-oxygen analysis from texture ice, (*7*) on radiocarbon analysis from the enclosing sediments and $^{14}$C-dates; Roman numerals indicate levels of ice wedges (I–IV).

wedge and the adjacent ice schliers have a heavier isotope composition (–16.1%).

We observe similar trends when comparing the oxygen isotope diagram obtained from samples from the multi-level complex of the Late Pleistocene ice wedges of Ayon Island (Fig. 5, A) with a diagram of wedges from the Plakhinskii Yar yedoma in the lower reaches of the Kolyma (Fig. 5, B); the deposits there are dated from 30 to 11 ka BP, and the ice wedges with direct AMS-dating from 27 to 11 ka BP (Vasil'chuk et al., 2004). Both diagrams identify four cycles: (a) 15 to 12 ka BP with the mean value of $\delta^{18}O$ = –31.1‰ (the depth was 2.7 to 1.8 m); (b) 20 to 15 ka BP with the mean value of $\delta^{18}O$ = –32.6‰ (the depth was 8.1 to 4.0 m); (c) 26 to 20 ka BP with the mean value of $\delta^{18}O$ = –33.0‰ (the depth was 12.2 to 8. 6 m); (d) 30 to 26 ka BP with the mean value of $\delta^{18}O$ = –33.8‰ (the depth was 13.2 to 14.5 m). At a depth of 12 and 6 m in the Plakhinskii Yar section peaks occur in the salt distribution. Here, the dry residue exceeds 0.2%, with peaks represented by a series of determinations, rather than single values (Vasil'chuk, 1992).

Modern ice wedges on Ayon laida have values of $\delta^{18}O$ from –23.0 to –18.6‰. In 1996–2000 at the Ayon weather station in the framework of the SNIP (Siberian Network of Isotopes in Precipitation) program, atmospheric precipitation was sampled for isotope analysis. The averaged values of $\delta^{18}O$ in the precipitation were –21.09‰ and the values of $\delta^{2}H$ were –169.3‰ (Kurita et al., 2004). These values are comparable with the data on the average isotope composition of modern and Holocene ice wedges, since they are obtained mainly for the precipitation of the winter season.

Deposits containing and underlying the ice wedges have a low content of highly soluble salts in an aqueous extract. In the underlying sand layer, their sum does not exceed 0.05% (Table 4). In the yedoma deposits, these values range from 0.46% at the base of the sandy loam to 0.07% at the top, with an average of 0.2%. The chemical composition of the aqueous extract is char-

**Table 2.** Radiocarbon dates for Late-Pleistocene and Holocene deposits on Ayon Island

| Section, Sample ID | Altitude/depth, m | Material | Conventional age, $^{14}C$ yr | Age, calibrated yr | Lab ID |
|---|---|---|---|---|---|
| Late-Pleistocene yedoma deposits | | | | | |
| 337-YuV/2 | +30.5 | Roots | 10180 ± 280 | 10743–9210 | (GIN-4967) |
| 337-YuV/16 | +8.5 | The same | 28600 ± 1000 | 32771–29046 | (GIN-4968) |
| 337-YuV/3 | +9.0 | The same | 28100 ± 800 | 31925–28983 | (GIN-4969) |
| Holocene deposits, according to (*Noveishie otlozheniya*..., 1980) | | | | | |
| Flood plain of the brook | 0.5 | Peat | 1280 ± 20 | 672–770 | MGU-583 |
| Archeological site, the west coast | 0.2 | Wood | 1400 ± 125 | 387–940 | MGU-598 |
| | 0.5 | Coal | 1470 ± 125 | 256–860 | MGU-597 |
| The northwest coast, ancient alases | 0.5 | The same | 5680 ± 900 | 6685–2472 | MGU-595 |
| Ancient alases* | 1.5 | Peat | 6920 ± 110 | 6003–5636 | MGU-596 |
| Ancient alases* | 0.2 | The same | 8470 ± 140 | 7936–7084 | MGU-601 |
| Vyveem River, The settlement of Leningradskii* | 6–7 | The same | 33700 ± 800 | 38081–34233 | MGU-338 |
| | 3–4 | The same | 7890 ± 120 | 7067–6486 | MGU-273 |

* According to (Tarakanov et al., 1974).

acterized by the predominance of chlorides and hydrocarbonates in the anions, and sodium and potassium in the cations. The ratio of the chloride ion to the sulphate ion in the sand formation does not exceed 2.2 (Fig. 6), while in the formation of sandy loams at the absolute elevations of +8 and +13 m two peaks are noted, where this ratio is 8.5 and 7.2, respectively, while the content of highly soluble salts in these sandy loam has average cross-sectional values.

The mineralization of ice wedges corresponds to ultra-fresh ice (36–106 mg/L) (Table 5). Among the anions, bicarbonate ion dominates, while among cations sodium and potassium ions dominate. The chemical composition of water from lakes at the high and low laida, the polygonal groove at the high laida, the snow patch, and sea ice were compared. The results showed that chemical content of ice wedges is similar to the snow patch and differs much from lakes, the groove, and sea ice. The chemical composition of the ice shows its predominantly atmospheric origin. The ratio of chlorine and sulfate ions is stable, slightly increasing upward (Fig. 6). A comparison with the enclosing sediments indicates that the lower part of the sandy loam (from +3 to +13 m) was accumulated with periodic sea water being involved: two maxima are noted (8.5 and 7.2 at the +8.0 and +13.0 m above sea level, respectively), while during the formation of the upper part of the sediments the effect of sea water was significantly reduced; the values of this index lie in the range are 0.6–2.7.

To determine the seawater effect on the composition of ice wedges, enzymatic (proteolytic) activity was analyzed in 12 samples. The values obtained were from 30 to 216 enzyme units (e.u.) per 1 L. In the modern fragment of the ice vein on the Ayon Island laida, the proteolytic activity was 82 e.u. per 1 L, while in the sample of floating ice at sea it was 130 e.u. per 1 L; in fresh lake water the values of the proteolytic activity were 20 e.u. per 1 L. The highest proteolytic activity in the section was recorded in the ice wedges of the lower level, 216 e.u. per 1 L. The data may indicate that the lower level of the ice wedges was formed with marine aerosols being involved. In the middle part of the profile, the values of proteolytic activity range from 30 to 112 e.u. per L. This may indicate a periodic change in the role of marine aerosols in the formation of ice wedges.

Diatom flora was determined in the yedoma deposits: 14 freshwater and freshwater brackish water diatom species and 1 marine species (*Melosira sulcata*), as a rule, with single occurrence estimates (*Noveishie otlozheniya*..., 1980). Soil complexes of diatoms at 28.0 and 11.5 m depth indicate at least a two-time drainage of the reservoir. The results of analysis of fauna of beetles from the yedoma indicate a single change of open landscapes of dry tundra with mesophilic landscapes with a wide spread of shrubs and

**Table 3.** Variations in $\delta^{18}O$ values in the Late-Pleistocene (pIW) and Holocene (hIW) ice wedges and segregated ice schlieres (SIS) ices of Ayon Island

| Sample ID | Sampling altitude, m | $\delta^{18}O$, ‰ | Type of ice | Sample ID | Sampling altitude, m | $\delta^{18}O$, ‰ | Type of ice |
|---|---|---|---|---|---|---|---|
| Syngenetic Late-Pleistocene ice wedges in the yedoma | | | | | | | |
| 337-YuV/33 | +15.5 | –29.9* | pIW | 337-YuV/65 | +24.0 | –29.5 | pIW |
| 337-YuV/34 | +15.3 | –29.4 | | 337-YuV/77 | +5.0 | –30.2 | |
| 337-YuV/35 | +15.1 | –29.6 | | 337-YuV/78 | +5.4 | –34.0* | |
| 337-YuV/36 | +15.0 | –29.6 | | 337-YuV/79 | +5.9 | –31.1 | |
| 337-YuV/37 | +14.8 | –29.9 | | 337-YuV/80 | +6.2 | –31.7 | |
| 337-YuV/38 | +14.6 | –31.1* | | 337-YuV/81 | +6.5 | –30.8 | |
| 337-YuV/39 | +14.4 | –31.0 | | 337-YuV/82 | +6.7 | –30.5 | |
| 337-YuV/40 | +13.6 | –30.0 | | 337-YuV/83 | +7.0 | –31.8* | |
| 337-YuV/41 | +13.5 | –30.0 | | 337-YuV/84 | +6.5 | –30.6 | |
| 337-YuV/42 | +13.3 | –29.5 | | 337-YuV/85 | +7.0 | –30.9* | |
| 337-YuV/43 | +13.0 | –29.4 | | 337-YuV/86 | +7.5 | –30.5 | |
| 337-YuV/44 | +16.0 | –30.5 | | 337-YuV/87 | +8.0 | –30.6 | |
| 337-YuV/45 | +16.2 | –31.0* | | 337-YuV/88 | +8.5 | –30.8 | |
| 337-YuV/46 | +16.4 | –28.7 | | 337-YuV/89 | +9.0 | –32.3* | |
| 337-YuV/47 | +16.7 | –30.1 | | 337-YuV/90 | +9.5 | –31.0 | |
| 337-YuV/48 | +17.0 | –31.2 | | 337-YuV/91 | +9.6 | –31.3 | |
| 337-YuV/50 | +17.7 | –29.4 | | 337-YuV/92 | +10.0 | –31.1 | |
| 337-YuV/51 | +18.0 | –29.3 | | 337-YuV/93 | +11.0 | –32.5* | |
| 337-YuV/52 | +18.4 | –29.6 | | 337-YuV/94 | +12.0 | –31.1 | |
| 337-YuV/53 | +19.0 | –29.6 | | 337-YuV/95 | +13.0 | –32.9* | |
| 337-YuV/54 | +19.3 | –29.5 | | 337-YuV/96 | +14.0 | –30.2 | |
| 337-YuV/55 | +19.3 | –29.0 | | 337-YuV/97 | +14.5 | –30.9 | |
| 337-YuV/56 | +19.5 | –29.2 | | 337-YuV/99 | +15.5 | –31.7* | |
| 337-YuV/57 | +19.8 | –28.9 | | 337-YuV/100 | +16.0 | –30.6 | |
| 337-YuV/58 | +20.2 | –29.7 | | 337-YuV/101 | +16.5 | –30.4 | |
| 337-YuV/59 | +20.5 | –29.5* | | 337-YuV/102 | +17.0 | –30.6 | |
| 337-YuV/60 | +21.0 | –28.9 | | 337-YuV/104 | +18.0 | –32.2* | |
| 337-YuV/61 | +13.5 | –28.4* | | 337-YuV/105 | +18.7 | –30.0 | |
| 337-YuV/62 | +13.0 | –30.8 | | 337-YuV/106 | +19.5 | –30.2 | |
| 337-YuV/63 | +12.5 | –30.6 | | 337-YuV/107 | +23.0 | –29.3 | |
| 337-YuV/64 | +12.0 | –30.1 | | | | | |
| Syngenetic Late-Pleistocene segregated ice schlieres in the yedoma stratum | | | | | | | |
| 337-YuV/3 | +19.4 | –31.2 | SIS | 337-YuV/9 | +24.0 | –30.0 | SIS |
| 337-YuV/4 | +20.9 | –30.0 | | 337-YuV/20 | +9.5 | –30.2 | |
| 337-YuV/5 | +20.1 | –29.0 | | 337-YuV/21 | +8.0 | –30.0 | |
| 337-YuV/7 | +15.0 | –29.0 | | 337-YuV/24 | +5.5 | –29.7 | |
| 337-YuV/8 | +13.0 | –29.9 | | | | | |
| Syngenetic Holocene ice wedges in the peat patch | | | | | | | |
| 337-YuV/66 | +27.0 | –21.5 | hIW | 337-YuV/70 | +29.0 | –22.1 | hIW |
| 337-YuV/66 | +27.5 | –21.2 | | 337-YuV/71 | +29.3 | –22.3 | |
| 337-YuV/66 | +28.0 | –21.7 | | 337-YuV/72 | +29.0 | –21.7 | |
| 337-YuV/66 | +28.5 | –21.0 | | 337-YuV/74 | +29.4 | –21.1 | |
| Edge of Holocene ice wedges and ice schlieres of ice in the peat patch | | | | | | | |
| 337-YuV/73 | +29.0 | –22.1 | Edge | 337-YuV/10 | +27.9 | –16.1 | SIS |

* Isotope analysis was performed at the Institute of Water Problems, RAS, the other samples were analyzed at the Institute of Geology, the city of Tallinn.

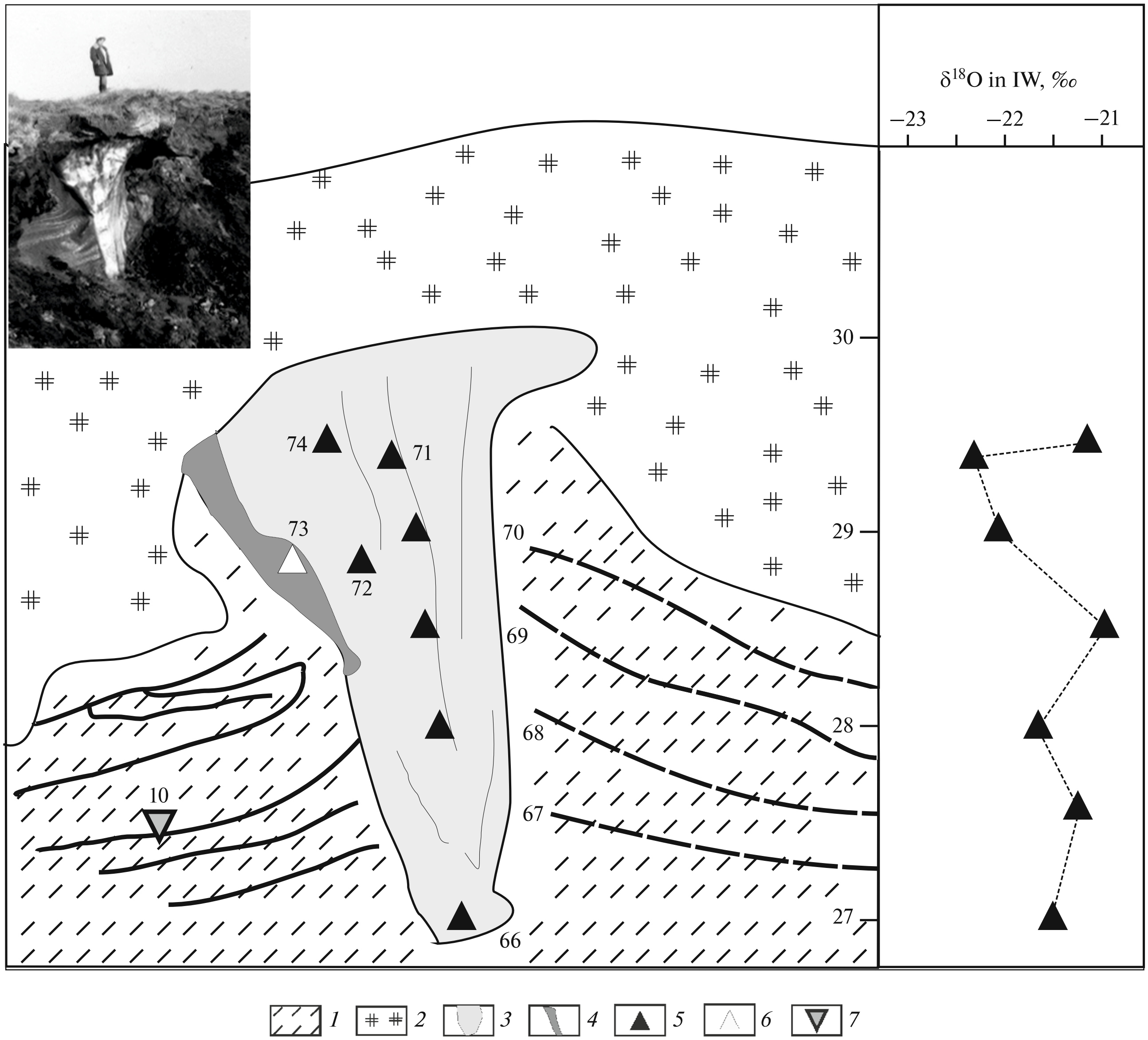


**Fig. 4.** Cryolithological structure of the Holocene peat inset at the top of the Ayon yedoma. Scheme of sampling and oxygen isotope diagram of Holocene ice wedges: (*1*) sandy loam; (*2*) peat; (*3*) ice-wedge; (*4*) ice from ice-wedge edging; (*5–7*) ice sampling points for isotope analysis: (*5*) from the Holocene ice wedge, (*6*) from the ice-wedge edging, (*7*) from the ice schliers.

later landscapes of a characteristic cryoxorotic appearance. Similar changes in the fauna of beetles were recorded in the section of the Duvanny Yar yedoma in Kolyma.

Based on the results of analytics, for all of the period of accumulation of yedoma deposits on Ayon Island the facies situation had been changing: subaquatic conditions were replaced by subaerial conditions, which is shown by diatom analysis data. At least 2 short periods of an increasing role of marine aerosols in the formation of a yedoma cyclite containing a third ice-wedge level have been noted

**Reconstruction of the winter temperature.** To compare with the Ayon data, the authors reconstructed the values of the mean-winter and mean-January temperatures in sections of Chaun-Chukotka, which are compared with the data on the Plakhinskii Yar section in the lower reaches of the Kolyma River. The isotope composition of the Late Pleistocene syngenetic ice wedges in several locations of the Chaun-Chukotka has been studied by A.N. Kotov: in the mouth of the Rauchua River on the coast of the East Siberian Sea, on the Ekityki River, and in the middle reaches of the Amguema River at Wrangel Island (Kotov, 1998, 1999a, 1999b). Reconstructions of the mean January ($t_{m.J}$) and mean winter ($t_{m.w}$) temperatures were made on the basis of a comparison of the isotope composition of modern veins ($\delta^{18}O_{ice\ vein}$) and the modern win-

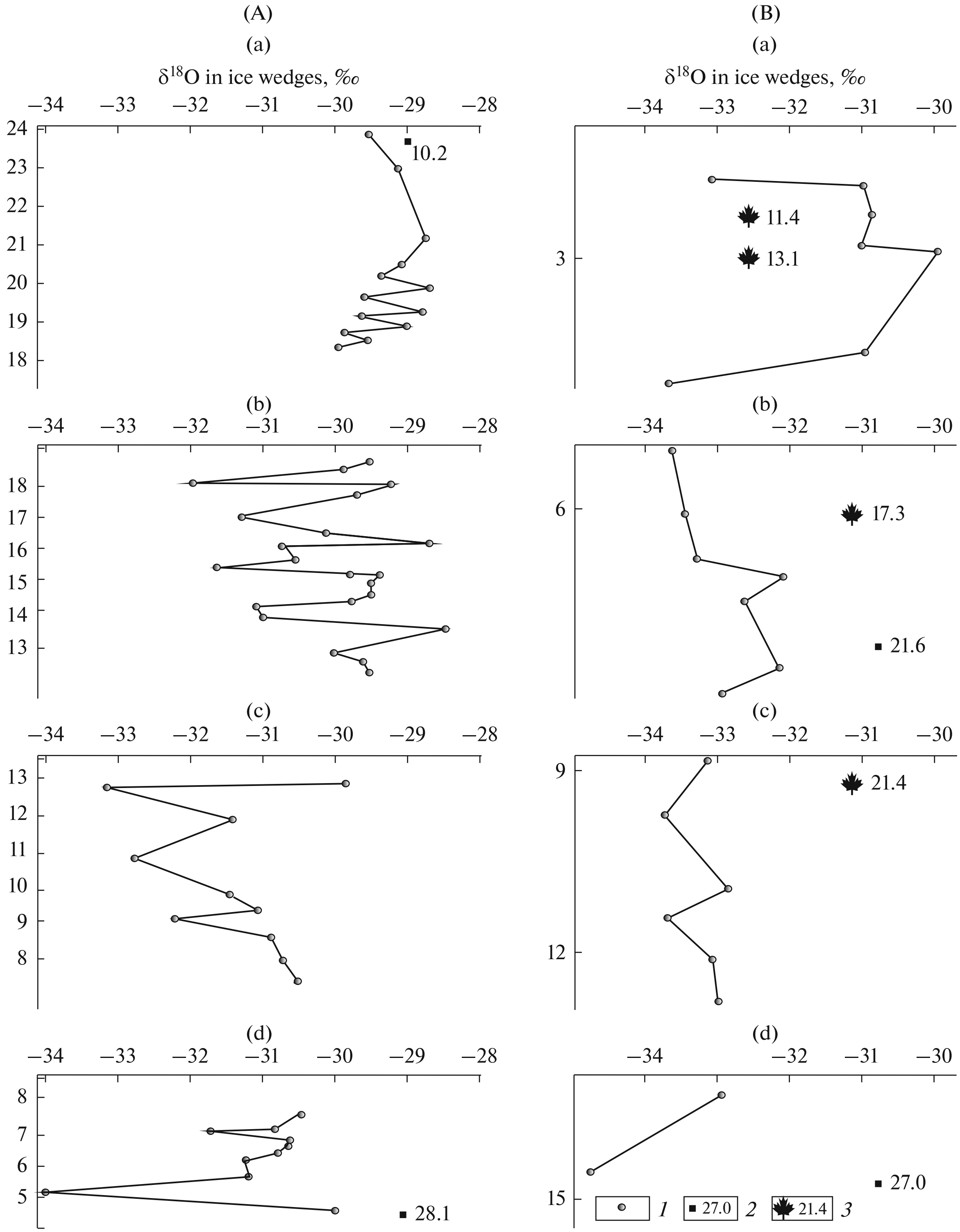


**Fig. 5.** Oxygen isotope diagrams of four levels of the Late Pleistocene ice wedges of the Ayon yedoma (A) and of the Plakhinskii Yar yedoma (B), that were formed from 30 to 12 ka BP. Fragments of ice wedges with different age were identified in Ayon yedoma: (a) 15–20 ka BP with mean value of $\delta^{18}O$ = –29.6‰ (18–23 m above sea level); (b) 20–15 ka BP with the mean value of $\delta^{18}O$ = –30.5‰ (13–18 m above sea level); (c) 26–20 ka BP with the mean value of $\delta^{18}O$ = –31.6‰ (8–13 m above sea level); (d) 30–26 ka BP with the mean value of $\delta^{18}O$ = –31.7‰ (5–8 m above sea level); (*1*) values of $\delta^{18}$ O (‰); (*2*) $^{14}C$-dating from the enclosing sediments; (*3*) AMS $^{14}C$-dating from ice wedges.

**Table 4.** The composition and content of water-soluble salts in the syngenetic permafrost deposits of the 25–30-m Late-Pleistocene yedoma of Ayon Island

| Sample ID | Sampling altitude, m | Total dissolved solids, % | Major cations and anions concentration, % | | | | | | pH |
|---|---|---|---|---|---|---|---|---|---|
| | | | $HCO_3^-$ | $Cl^-$ | $SO_4^{2-}$ | $Ca^{2+}$ | $Mg^{2+}$ | $Na^+ + K^+$ | |
| 337-YuV/9 | +24.0 | 0.074 | 0.015 | 0.010 | 0.016 | 0.002 | 0.001 | 0.016 | 7.56 |
| 337-YuV/4 | +20.9 | 0.105 | 0.026 | 0.026 | 0.017 | 0.008 | 0.002 | 0.022 | 7.90 |
| 337-YuV/5 | +20.1 | 0.137 | 0.026 | 0.034 | 0.029 | 0.012 | 0.004 | 0.026 | 7.76 |
| 337-YuV/6 | +19.8 | 0.160 | 0.027 | 0.044 | 0.032 | 0.015 | 0.001 | 0.036 | 7.81 |
| 337-YuV/14 | +19.5 | 0.214 | 0.029 | 0.058 | 0.045 | 0.013 | 0.007 | 0.042 | 7.15 |
| 337-YuV/3 | +19.4 | 0.093 | 0.011 | 0.030 | 0.011 | 0.006 | 0.003 | 0.017 | 7.26 |
| 337-YuV/15 | +16.5 | 0.177 | 0.034 | 0.035 | 0.038 | 0.013 | 0.005 | 0.029 | 7.86 |
| 337-YuV/17 | +14.5 | 0.153 | 0.040 | 0.031 | 0.020 | 0.011 | 0.005 | 0.023 | 8.05 |
| 337-YuV/7 | +15.0 | 0.182 | 0.049 | 0.035 | 0.029 | 0.009 | 0.003 | 0.040 | 8.18 |
| 337-YuV/8 | +13.0 | 0.165 | 0.049 | 0.036 | 0.005 | 0.010 | 0.003 | 0.027 | 8.16 |
| 337-YuV/18 | +13.0 | 0.205 | 0.032 | 0.039 | 0.044 | 0.016 | 0.006 | 0.029 | 7.81 |
| 337-YuV/19 | +11.0 | 0.200 | 0.046 | 0.033 | 0.016 | 0.019 | 0.008 | 0.009 | 7.84 |
| 337-YuV/20 | +9.5 | 0.166 | 0.046 | 0.022 | 0.010 | 0.015 | 0.006 | 0.008 | 7.82 |
| 337-YuV/21 | +8.0 | 0.218 | 0.024 | 0.034 | 0.004 | 0.012 | 0.005 | 0.011 | 6.44 |
| 337-YuV/22 | +7.0 | 0.462 | 0.043 | 0.086 | 0.066 | 0.039 | 0.015 | 0.031 | 7.60 |
| 337-YuV/23 | +5.0 | 0.052 | 0.015 | 0.011 | 0.005 | 0.005 | 0.001 | 0.007 | 7.33 |
| 337-YuV/25 | +3.0 | 0.040 | 0.012 | 0.011 | 0.005 | 0.004 | 0.001 | 0.007 | 7.24 |

ter temperature for the period of formation of the ice wedges, i.e., the last 60 to 100 years (Table 6) (Vasil'chuk, 1992); they were obtained via two equations:

$$t_{m.J} = 1.5\delta^{18}O_{ice\ vein}(\pm 3°C)$$
$$\text{and } t_{m.w} = \delta^{18}O_{ice\ vein}\ (\pm 2°C).$$

The winter air temperature for several sections of Chaun-Chukotka (Table 7) are calculated from these equations.

During the accumulation of ice wedges in the mouth of the Rauchua River and in the valley of the Ekityk River (nos. 5, 6 in Fig. 1) for 45000 to 30000 years ago the mean winter temperature was lower than the modern temperature by 7 to 9°C, and the mean January temperature was 19 to 14°C lower. For the period of 30 to 26 ka BP at Ayon Island, when the ice wedges of the lower fourth level were forming, the mean winter temperature was lower than the modern one by 11°C and the mean January temperature was 17 °C lower; however, if we consider the minimum value of $\delta^{18}O$ in ice wedges (–34‰) the difference with the modern mean January temperature reached 21°C. For Plakhinskii Yar, the mean winter temperature was lower than the modern one by 10°C, and the mean January temperature by 15°C, the same values for this period on the Kotelny Island were 10°C and 14°C (Vasil'chuk et al., 2016). Obviously, the lowest values of the mean winter and mean January temperatures correspond to a period of a significant decrease in winter temperatures of 29 000–28 000 years ago

During the 26–20 ka BP period the mean temperature on Ayon Island differed from the modern one by 18°C, from the mean winter temperature by 12°C, and

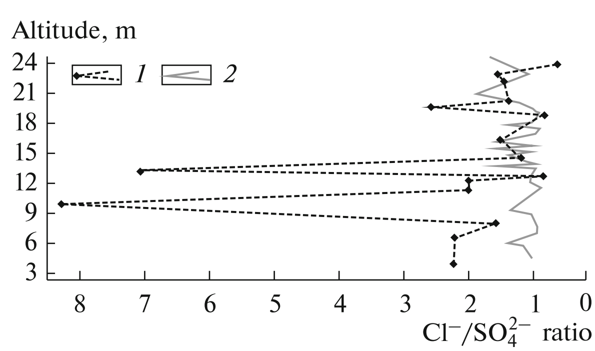


**Fig. 6.** The ratio of $Cl^-$ to $SO_4^{2-}$ in the enclosing sediments (*1*) and in the Late Pleistocene syngenetic ice wedges (*2*) of Ayon yedoma.

**Table 5.** Composition and content of water-soluble salts in the syngenetic ice wedges of the 25–30-m Late-Pleistocene yedoma and in the modern ices and the water reservoirs of Ayon Island

| Sample ID | Sampling altitude, m | Total dissolved solids, mg/L | Major cations and anions concentration, mg/L | | | | | | pH |
|---|---|---|---|---|---|---|---|---|---|
| | | | $HCO_3^-$ | $Cl^-$ | $SO_4^{2-}$ | $Ca^{2+}$ | $Mg^{2+}$ | $Na^+ + K^+$ | |
| Syngenetic ice wedges | | | | | | | | | |
| 337-YuV/65 | +24.0 | 82 | 49 | 16 | 12 | 11 | 4 | 15 | 7.47 |
| 337-YuV/107 | +23.0 | 60 | 34 | 7 | 13 | 7 | 2 | 12 | 7.48 |
| 337-YuV/58f | +20.2 | 104 | 61 | 20 | 12 | 5 | 4 | 28 | 7.87 |
| 337-YuV/58 | +20.2 | 80 | 46 | 12 | 18 | 5 | 2 | 23 | 7.52 |
| 337-YuV/57 | +19.8 | 70 | 45 | 5 | 12 | 9 | 1 | 14 | 7.64 |
| 337-YuV/55 | +19.3 | 90 | 52 | 8 | 23 | 10 | 4 | 18 | 7.42 |
| 337-YuV/53 | +19.0 | 78 | 46 | 9 | 17 | 8 | 3 | 16 | 7.63 |
| 337-YuV/52 | +18.4 | 66 | 37 | 8 | 12 | 7 | 2 | 14 | 7.20 |
| 337-YuV/104 | +18.0 | 84 | 37 | 17 | 17 | 8 | 4 | 16 | 7.50 |
| 337-YuV/103 | +17.5 | 88 | 49 | 9 | 19 | 9 | 3 | 17 | 7.58 |
| 337-YuV/102 | +17.0 | 54 | 28 | 6 | 12 | 4 | 2 | 12 | 7.35 |
| 337-YuV/46 | +16.4 | 108 | 67 | 18 | 16 | 9 | 5 | 24 | 7.65 |
| 337-YuV/45 | +16.2 | 74 | 43 | 9 | 16 | 9 | 3 | 16 | 7.65 |
| 337-YuV/44 | +16.0 | 54 | 33 | 9 | 8 | 6 | 2 | 12 | 7.38 |
| 337-YuV/100 | +16.0 | 70 | 49 | 7 | 12 | 7 | 2 | 17 | 7.46 |
| 337-YuV/33 | +15.5 | 106 | 61 | 18 | 17 | 8 | 5 | 24 | 7.00 |
| 337-YuV/34 | +15.3 | 56 | 40 | 7 | 8 | 7 | 2 | 12 | 7.07 |
| 337-YuV/35 | +15.1 | 44 | 15 | 8 | 11 | 6 | 3 | 4 | 7.52 |
| 337-YuV/98 | +15.0 | 48 | 28 | 7 | 10 | 5 | 1 | 12 | 7.63 |
| 337-YuV/37 | +14.8 | 68 | 37 | 9 | 16 | 5 | 2 | 18 | 7.63 |
| 337-YuV/38 | +14.6 | 70 | 55 | 8 | 7 | 9 | 3 | 13 | 7.41 |
| 337-YuV/39 | +14.4 | 58 | 34 | 6 | 11 | 5 | 1 | 14 | 7.40 |
| 337-YuV/96 | +14.0 | 50 | 24 | 7 | 10 | 3 | 3 | 10 | 7.40 |
| 337-YuV/40 | +13.6 | 68 | 33 | 9 | 15 | 7 | 2 | 15 | 7.13 |
| 337-YuV/61 | +13.5 | 50 | 34 | 5 | 8 | 8 | 1 | 9 | 7.12 |
| 337-YuV/41 | +13.5 | 76 | 49 | 9 | 10 | 11 | 1 | 15 | 7.52 |
| 337-YuV/42 | +13.3 | 104 | 49 | 12 | 26 | 11 | 1 | 24 | 7.67 |
| 337-YuV/36 | +13.0 | 58 | 35 | 9 | 10 | 4 | 3 | 14 | 7.47 |
| 337-YuV/43 | +13.0 | 64 | 37 | 11 | 8 | 7 | 1 | 15 | 7.48 |
| 337-YuV/63 | +12.5 | 62 | 37 | 7 | 13 | 5 | 4 | 11 | 7.06 |
| 337-YuV/64 | +12.0 | 50 | 28 | 7 | 11 | 6 | 2 | 10 | 7.27 |
| 337-YuV/94 | +12.0 | 48 | 18 | 6 | 15 | 5 | 1 | 9 | 7.35 |
| 337-YuV/89f | +9.0 | 36 | 21 | 5 | 5 | 4 | 2 | 5 | 6.86 |
| 337-YuV/89 | +9.0 | 44 | 24 | 5 | 8 | 5 | 1 | 8 | 7.30 |
| 337-YuV/85 | +7.0 | 36 | 15 | 5 | 9 | 4 | 1 | 7 | 6.75 |
| 337-YuV/83 | +7.0 | 36 | 14 | 5 | 9 | 4 | 1 | 7 | 7.15 |
| 337-YuV/82 | +6.7 | 42 | 18 | 7 | 7 | 5 | 3 | 4 | 6.92 |
| 337-YuV/79 | +5.9 | 62 | 28 | 10 | 13 | 7 | 1 | 13 | 7.23 |
| 337-YuV/77 | +5.0 | 54 | 15 | 8 | 14 | 6 | 1 | 10 | 6.95 |
| Modern sea ice, snow patch, and lakes | | | | | | | | | |
| Sea ice floe | 0.0 | 1138 | 9 | 673 | 27 | 5 | 25 | 399 | 6.35 |
| Lake, high laida | +2 | 50 | 21 | 14 | 5 | 3 | 3 | 10 | 7.05 |
| Lake, low laida | +0.5 | 1238 | 119 | 741 | 24 | 126 | 122 | 160 | 7.63 |
| Water from the polygonal groove at the high laida | +1.5 | 318 | 12 | 185 | 7 | 14 | 13 | 87 | 6.4 |
| Snow patch | +1.5 | 48 | 12 | 7 | 12 | 2 | 0.1 | 13 | 7.33 |

**Table 6.** Values of $\delta^{18}O$ in the ice veinlets of modern syngenetic ice wedges on Ayon Island, in northern Chukotka and on the neighboring islands of Eastern Arctic of Russia, according to (Vasil'chuk, 1992) with additions

| Location of modern ice veinlets and coordinates | $\delta^{18}O_{v.gr}$, ‰ | $\sum t^{\circ}_{w}$, | $t_{m.w}$ | $t_{m.J}$ | $t_{soil}$ |
|---|---|---|---|---|---|
| Ayon Island (69°47′ N, 168°39′ E) | –20.0 | –5047 | –20 | –29 | –12 |
| Mouth of the Rauchua River ( 69°30′ N, 166°43′ E) | –22.0 | –5436 | –21 | –32 | –13 |
| The Kuvet River ( 69°16′ N, 175°02′ E) | –21.0 | –4700 | –18 | –27 | –11 |
| Wrangel Island (71°14″ N, 179°24″ W) | –20.0 | –4272 | –17 | –25 | –11 |
| The Amguema River (67°03′ N, 178°53′ W) | –19.0 | –4992 | –19 | –29 | –11 |
| Koolen Island (65°59′ N, 170°58′ W) | –16.0 | –3400 | –14 | –22 | –7 |
| Lake Elgygytgyn ( 67°30″ N, 172°00″ E) | –20.4 | –4598 | –18 | –27 | –10 |
| Henrietta Island (77°06′ N, 156°30′ E) | –15.3 | –5330 | –17 | –27 | –12 |
| Zhokhov Island (76°09′ N, 152°43′ E) [5] | –20.0 | –5363 | –18 | –29 | –13 |
| Kotelny Island (75°27′ N, 140°50′ E) | –18.1 | –5408 | –19 | –29 | –14 |
| Bunge Land (75°24′ N, 141°16′ E) [4] | –17.6 | –5989 | –21 | –28 | –14 |
| Maly Lyakhovsky Island (74°07′ N, 140°40′ E) | –18.0 | –5408 | –20 | –31 | –14 |
| Bolshoy Lyakhovsky Island – the south (74°07′ N, 140°40′ E) [4] | –20.4 | –5400 | –20 | –31 | –14 |
| New Siberia Island (75°03′ N, 148°28′ E) | –18.0 | –5500 | –20 | –30 | –14 |
| Chetyryokhstolbovoy (70°47′ N, 161°36′ E) | –20.0 | –5143 | –19 | –30 | –13 |
| Plakhinskii Yar (70°47′ N, 161°36′ E) | –25.0 | –5733 | –23 | –35 | –13 |

$\delta^{18}O_{v.gr}$, the values of $\delta^{18}O$ in growths of ice wedges (‰ to SMOW); $\sum t^{\circ}_{w}$, the sum of winter temperatures (deg days); $t_{m.w}$, the average-winter temperature of the air (°C); $t_{m.J}$, the average January temperature of the air (°C); $t_{soil}$, the average annual temperature of the soil (°C), the snow and vegetation cover is removed.

in the Plakhinskii Yar area by 14°C and 10°C, respectively; in the middle reaches of the Amguema River these values are close to the difference in temperature values in the Plakhinskii Yar area, 14°C and 9°C, respectively. It should be noted that on Ayon Island for the period from 26 to 20 ka BP, as before, the difference between the reconstructed and the modern temperature is at a maximum. In the period from 20 to 15 ka the mean temperature on Ayon Island differed from the modern case by 17°C and the mean winter values differed by 10°C; for Plakhinskii Yar these indicators were 13°C and 9°C and for the yedoma of Kotelny Island (Vasil'chuk et al., 2016) it reached 8°C and 6°C. For the period from 15 to 12 ka BP the difference in the mean January and mean winter temperatures in comparison with the current temperature was 15°C and 10°C for Ayon Island; and 11°C and 8°C, respectively, for Plakhinsky Yar; while Wrangel Island data showed a very noticeable difference compared to the modern temperatures on the island: 18°C and 12°C.

The noted differences in the mean winter and mean January temperature, compared with modern temperatures, suggest that Ayon Island during the Late Pleistocene was in a much colder climate (most likely in the absence of the warming effect of the sea), and the conditions of the winter season there were much more severe. The Late Pleistocene mean temperature on the island reconstructed from the values of $\delta^{18}O$ in ice wedges at Ayon Island was from –50 to –44°C (the modern mean-January temperature is –28.7°C) and the mean winter temperature was from –34 to –29°C (with a current mean winter temperature of –19.4°C).

Interpolation of radiocarbon data of the Ayon Island yedoma showed that the lowest temperatures occurred from 21 to 18 ka BP and from 29 to 28 ka BP, which corresponds to the global cooling periods (Heinrich's events No. 3 and No. 2 (Vasil'chuk, 2003). Coming from the Late Pleistocene to the Holocene, the difference in the mean winter temperature at Ayon Island was 9 to 10°C, and the mean January difference was from 13 to 15°C, while the same values for Plakhinskii Yar were 6°C and 9°C, respectively. This was probably caused by configuration changes of the shoreline and the transition of the of Ayon territory from the continental to the island area, because of the rise in sea level. Therefore Ayon Island became an island only at the end of the Pleistocene–Early Holocene. This is shown by the change in the conditions of the winter season. The mean winter and mean January temperature in the first half of the Holocene (10–5 ka BP) on Ayon Island was usually 2°C lower than today. The mean winter temperature on Lake El'gygytgyn, Plakhinskyii Yar, and Wrangel Island has increased the most compared to this period (Table 7).

**Table 7.** The values of $\delta^{18}O$ in the ice wedges of northern Chukotka and paleotemperature characteristics during the Late Pleistocene and Holocene

| Name of key section | $\delta^{18}O_{vein}$, ‰ | Paleoreconstructions | | | | Modern values | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $\sum t^{\circ}_{w}$ | $t^{\circ}_{m.w}$ | $t^{\circ}_{m.J}$ | $t_{paleo\ soil}$ | $\delta^{18}O_{vein}$, ‰ | $\sum t^{\circ}_{w}$ | $t^{\circ}_{m.w}$ | $t^{\circ}_{m.J}$ | $t_{modern\ soil}$ |
| 45–30 ka | | | | | | | | | | |
| Mouth of the Rauchua River[1] | –30.5 | –7500 | –30 | –46 | –19 | –22 | –5436 | –21 | –32 | –13 |
| The Ekityki River, tributary of the Amguema River[2] | –25.9 | –6500 | –26 | –38 | –14 | –19 | –4990 | –19 | –29 | –11 |
| 30–26 ka | | | | | | | | | | |
| Ayon Island | –31.2 | –7750 | –31 | –46 | –19 | –20 | –5047 | –20 | –29 | –12 |
| Plakhinskii Yar | –33.8 | –8250 | –33 | –50 | –23 | –25 | –5733 | –23 | –35 | –13 |
| Kotelny Island | –29 | –7750 | –29 | –43 | –19 | –18 | –5408 | –19 | –29 | –14 |
| 26–20 ka | | | | | | | | | | |
| Ayon Island | –31.6 | –7800 | –32 | –47 | –20 | –20 | –5047 | –20 | –29 | –12 |
| Plakhinskii Yar | –33.0 | –8200 | –33 | –49 | –22 | –25 | –5733 | –23 | –35 | –13 |
| The Amguema River[3] | –28.0 | –7000 | –28 | –43 | –16 | –19 | –4992 | –19 | –29 | –11 |
| 20–15 ka | | | | | | | | | | |
| Ayon Island | –30.5 | –7500 | –30 | –46 | –19 | –20 | –5047 | –20 | –29 | –12 |
| Plakhinskii Yar | –32.6 | –8000 | –32 | –48 | –21 | –25 | –5733 | –23 | –35 | –13 |
| Kotelny Island | –25 | –6250 | –25 | –37 | –16 | –18 | –5408 | –19 | –29 | –14 |
| 15–12 ka | | | | | | | | | | |
| Ayon Island | –29.6 | –7400 | –30 | –44 | –18 | –20 | –5047 | –20 | –29 | –12 |
| Plakhinskii Yar | –31.1 | –7750 | –31 | –46 | –19 | –25 | –5733 | –23 | –35 | –13 |
| Wrangel Island[4] | –28.5 | –7000 | –29 | –43 | –17 | –20 | –4272 | –17 | –25 | –11 |
| 10–5 ka | | | | | | | | | | |
| Ayon Island | –21.6 | –5500 | –22 | –31 | –12 | –20 | –5047 | –20 | –29 | –12 |
| Wrangel Island[4] | –21.5 | –5400 | –22 | –30 | –12 | –20 | –4272 | –17 | –25 | –11 |
| Kotelny Island[6] | –22.5 | –5600 | –22 | –34 | –15 | –18 | –5408 | –19 | –29 | –14 |
| The Amguema River[3] | –20.0 | –5000 | –20 | –30 | –11 | –19 | –4992 | –19 | –29 | –11 |
| Lake Elgygytgyn[5] (bottom) | –23.5 | –5800 | –24 | –35 | –13 | –20.4 | –4598 | –18 | –27 | –10 |
| Lake Elgygytgyn[5] (top) | –22.4 | –5600 | –22 | –30 | –12 | –20.4 | –4598 | –18 | –27 | –10 |
| Plakhinskii Yar | –27 | –6750 | –27 | –40 | –15 | –25 | –5733 | –23 | –35 | –13 |

$\sum t^{\circ}_{w}$, total annual freezing index (deg days); $\delta^{18}O_{vein}$, the values of $\delta^{18}O$ in the corresponding fragment of ice wedges (‰ to SMOW); $t^{\circ}_{m.w}$, average-winter temperature (°C); $t^{\circ}_{m.J}$, the average January temperature (°C); $t_{paleo\ soil}$, average annual paleotemperature of soil (°C); $t_{modern\ soil}$, modern average annual temperature of soil (the snow and vegetation cover is removed) (°C). [1] (Kotov 1998c), [2] (Kotov 1999b), [3] (Kotov 1997), [4] (Kotov 1999a), [5](Schwamborn et al., 2006), [6] (Vasil'chuk et al., 2016).

## CONCLUSIONS

The special isotope characteristics and paleotemperature conditions on Ayon Island and adjacent areas of Northern Chukotka during the last 45000 years consist of:

• Almost identical trends in the distribution of the ice-wedge isotope characteristics of the Late Pleistocene ice on the island and in the lower reaches of the Kolyma River.

• The lowest values of the winter air temperature, according to the isotope characteristic of ice wedges were reached from 21 to18 ka BP and from 29 to 28 ka BP.

• A sharper shift towards less negative values of winter air temperature was noted during the transition from the Late Pleistocene to Holocene in comparison with the Nizhnekolymsk areas; it is associated with the effect of sea level change and the transition of the Ayon Island territory from the continental to the island state.

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